2.0 NWPCAM System

The NWPCAM is a national-level water quality model for simulating the water quality and economic benefits that result from various water pollution control policies. NWPCAM is designed to characterize water quality for the nation's network of rivers and streams and, to a more limited extent, its lakes. NWPCAM incorporates a national-scale water quality model into a system designed for conducting policy simulations and benefits assessments. NWPCAM is able to translate spatially varying water quality changes into terms that reflect the value that individuals place on water quality improvements. In this way, NWPCAM is capable of deriving benefit estimates for a wide variety of water pollution control policies.

NWPCAM's water quality modeling system is suitable for developing water quality estimates for virtually the entire inland portion of the country. Its national-scale framework allows hydraulic transport, routing, and connectivity of surface waters to be simulated in the 48 conterminous states. The model can be used to characterize source loadings (e.g., AFOs/CAFOs) under a number of alternative policy scenarios (e.g., loadings with controls). These loadings are processed through the NWPCAM water quality modeling system to estimate in-stream pollutant concentrations on a detailed spatial scale and to provide estimates of policy-induced changes in water quality. The model incorporates routines to translate water quality concentration estimates into measures of "beneficial use attainment"—categories including boating, fishing, and swimming—which are commonly used to characterize water quality for policy purposes. The model also calculates a six-parameter water quality index (WQI6) that provides a composite measure of overall water quality. Both the beneficial use attainment categories and the WQI6 estimates allow for the calculation of economic benefits associated with the estimated water quality improvements. NWPCAM can be used to assess both the water quality impacts and the social welfare implications of alternative policy scenarios.

NWPCAM is an evolving system developed for EPA's Office of Water (OW) by RTI and has been used in several applications to estimate the benefits of pollution control policies. An adaptation of version 1.0 was used by OW's Office of Waste Management (OWM) to evaluate the potential benefits of the Stormwater Phase II rulemaking (Bondelid, Ali, et al., 1999). Version 1.1 (RTI, 2000b), the version developed in response to external peer review on version 1.0, is a complete system oriented toward evaluating the effects of PS controls. NWPCAM version 1.1 was used in the recent Meat Processing Effluent Guidelines (http://www.epa.gov/ost/guide/mpp/). Version 1.5 was used in the proposed AFO/CAFO rule (RTI, 2000a). Version 1.6 was used in developing the final AFO/CAFO rule.

The foundation of NWPCAM 1.6 is the stream flow, transport, and flow-routing data obtained from the EPA Reach File 3 (RF3) database and the U.S. Geological Survey (USGS) Hydro-Climatic Data Network (HCDN). The RF3 database contains information about the nation's network of rivers and streams in the United States. As a national-scale model, NWPCAM's framework is limited to readily available national databases that can be accessed and processed using automated input and output file management procedures. Waterbody types currently included in NWPCAM 1.6 include free-flowing streams and rivers, lakes characterized by inflows and outflows from streams and rivers run-of-river reservoirs, and tidal rivers. Large, open water systems of estuaries (e.g., Chesapeake Bay), embayments (e.g., Waquoit Bay), coastal waters (e.g., New York Bight, Southern California Bight), the Great Lakes, and other large lakes (e.g., Lake Champlain) are *not* incorporated in the current framework of NWPCAM 1.6.

NWPCAM 1.6 consists of an Oralcle database that is manipulated through a series of Visual Basic modules, listed in Table 1. These modules perform analytical or simulation routines required for the overall modeling process. The modeling results are kept in Oracle tables and may be exported to an Oracle export file or other formats, including Microsoft Access.

Figure 1 presents a simplified flowchart of the NWPCAM 1.6 process employed for estimating the benefits of AFO/CAFO regulations using the Vaughn Water Quality Ladder (WQL) approach. The left-hand column of Figure 1 represents the main processes, and the right-hand columns represent integration of data and analytical modeling modules.

Table 1. NWPCAM 1.6 Modules

Preprocessing Routines

- Route and sequence RF3
- Define the RF3Lite subset for in-stream modeling
- Generate land-cover data set with routed and sequenced RF3
- Calculate slopes and sinuosity for RF3 reaches and land-use cells
- Route PS and combined sewer overflow (CSO) loads to the RF3Lite network
- Route NPS loads to the RF3 network
- Route NPS loads to the RF3Lite network

Modeling & Analysis Modules

- Distribute AFO/CAFO loads to agricultural cells using farm area and a random distribution method
- Route AFO/CAFO loads to the RF3 network
- Route AFO/CAFO loads to the RF3Lite network
- Model transport, decay, and transformation of pollutants in RF3Lite
- Calculate WQI6 and overall use support for each RF3Lite reach
- Calculate national use support summary
- Calculate local and nonlocal economic benefits for each state using the Vaughn WQL
- Calculate local and nonlocal economic benefits for each state using the WQI6

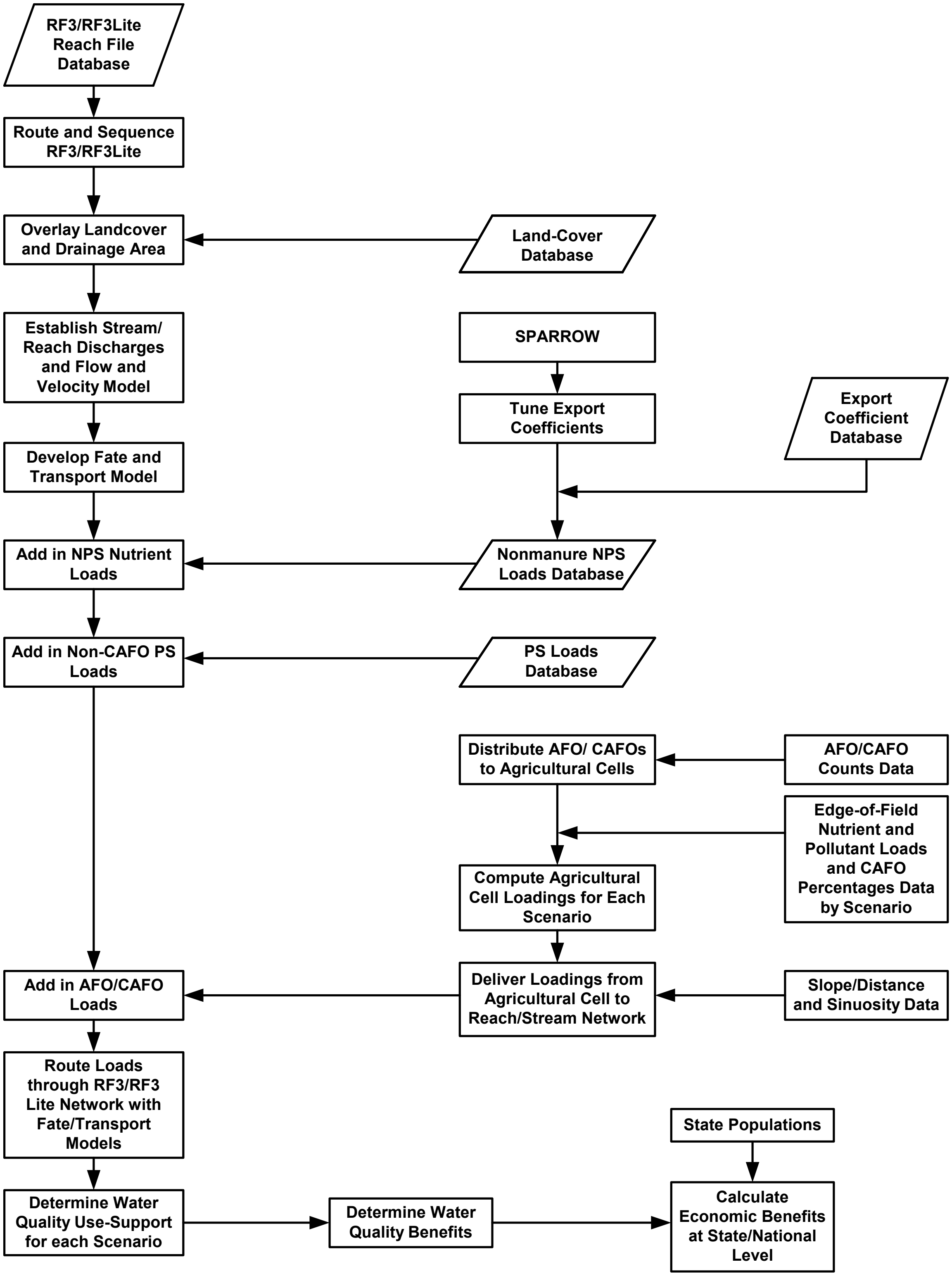

Figure 1. Overview of AFO/CAFO benefits analysis process.

2.1 Spatial and Environmental Databases

NWPCAM 1.6 relies on several extensive data sets to support the analytical routines developed to represent physical and chemical processes occurring within a watershed and along river reaches. Primary databases include (1) RF3 hydrologic and reach routing information; (2) land-use and land-cover information; (3) watershed and stream discharge information; (4) NPS nutrient export coefficients and other loading data; (5) PS pollutant loading information; and (6) AFO/CAFO loading information. Table 2 presents a listing of the principal data requirements for NWPCAM 1.6.

Table 2. Data Elements of NWPCAM 1.6

Tables	Report Section	Source
RF3 routing data (RF3RCHID, level, sequence number, stream order, routing parameters, open waters data, etc.)	2.2.1	U.S. EPA (2002a)
Land-use/land-cover data (land-use type, county Federal Information Processing Standards (FIPS) code, nearest reach and distance to nearest reach, sinuosity for each reach)	2.2.2	USGS (2002a)
8-digit hydrologic unit code (HUCs) (elevation, slope, discharge per km^2 per HUC based on USGS data drainage areas and discharges for watersheds)	2.2.3	ESRI (2000a) USGS (2002b)
AFO facility counts by county FIPS code for each animal operation type and size	3.2	U.S. EPA (2002b)
Percentage of AFOs considered as CAFOs by rulemaking scenario and state FIPS code	3.2	U.S. EPA (2002b)
AFO/CAFO edge-of-field nitrogen and phosphorus loadings by animal operation type and size	3.2	U.S. EPA (2002b)
AFO/CAFO edge-of-field pathogen indicator and sediment loadings by animal operation type and size	3.2	U.S. EPA (2002b)
Speciation factors for AFO/CAFO nitrogen and phosphorus loads	3.2	U.S. EPA (2002b)
Locations and loading data for industrial and municipal PSs	2.2.5	U.S. EPA (2002c, 2002d)
Combined sewer overflow (CSO) locations and loading data	2.2.5	U.S. EPA (1993)
NPs nutrient loadings based on land-use types and SPAtially Referenced Regression On Watershed (SPARROW) results	2.2.6	Smith et al. (1997)
Export coefficients for NPS of 5-day biochemical oxygen demand and sediment based on land use	Appendix A Table 1	Novotony and Olem (1994)
State population and RF3Lite segment length	Appendix A Table 2	ESRI (2000a; 2000b)

(continued)

Table 2. (continued)

Tables	Report Section	Source
Speciation factors for PS and NPS loadings	2.2.5	Metcalf & Eddy et al. (1991)
Modeling coefficients	Appendix A Table 3	U.S. EPA (1985)
Contribution of intermittent streams by hydroregion	RTI, 2001	RTI (2001)
Ratio of agricultural land slope to average slope by hydroregion	Appendix A Table 4	Calculated
Vaughn WQL threshold values	3.3.5	Vaughan (1986)
McClelland Water Quality Index (WQI)	3.3.7	McClelland (1974)

2.1.1 Hydrologic Routing File

The EPA Reach Files are a series of hydrologic databases that contain information on the U.S. surface waters. The Reach File databases were created to establish hydrologic ordering, to perform hydrologic navigation for modeling applications, and to provide a unique identifier for each surface water feature (i.e., the reach code). Reach codes uniquely identify the individual components of the nation's rivers and lakes. A reach represents a segment of a river or stream. Several segments may be linked together to characterize the total length and properties of a waterbody. The longer the river or stream, the more reaches are used to represent the full length of the waterbody. RF3 contains tabular data tables for routing, as well as full GIS coverages for mapping and data overlays. Currently, the best source for RF3 data is the BASINS Model developed by OW and the EPA Office of Science and Technology (OST) (U.S. EPA, 2002e).

NWPCAM 1.6 uses the RF3 network to move water and pollutants from a point of origin within the conterminous 48 states toward the major rivers and ultimately toward the discharge of these waters, which usually is to the oceans.

The RF3 network in NWPCAM 1.6 includes 1,817,988 reaches totaling 2,655,437 miles within the conterminous 48 states. The routing framework for Hydroregions 8 and 17 is only available from the first version of the Reach File (RF1) and includes 11,937 reaches totaling 90,253 miles.

A subset of the RF3 network (referred to as RF3Lite) was developed for in-stream modeling in NWPCAM 1.6. RF3Lite was defined as

- Streams >10 miles in length, and
- Small streams that are needed to connect streams >10 miles into a complete network.

RF3Lite maximizes the information available from RF3, while limiting the computational burden imposed on the full system. The RF3Lite network includes 577,068 reaches totaling 840,835 miles.

Hydrologic sequence numbers were assigned to RF3 reaches starting at the most upstream reach of a watershed and moving down the stream network. A small percentage of RF3 reaches were unable to be networked because they were (1) isolated reaches; (2) missed because of a discontinuity in the Reach File; or (3) located in an area with artificial reaches, channel, or swamp land. In the cases where a sequence number was not assigned to a reach, the reach was considered to have no connectivity with the network and was removed from the NWPCAM 1.6 database. Table 3 lists the key fields and field description of the RF3 routing data file.

Table 3. Key Fields of the RF3 Routing Data File

Field	Description
RF3RCHID	RF3 Reach ID
RUN_SEQUENCE	Hydrologic sequence number
STRM_ORDER	Stream order
CU	8-digit catalog unit
J_LEVEL	(Networked) stream junction level
N_LEVEL	(Networked) stream level
SEG_LENGTH	Segment length of the reach
SINU	Sinuosity

2.1.2 Land-Use/Land-Cover File

The USGS conterminous 48 states Land Cover Characteristics (LCC) Data Set version 2 forms the basis for the land-use/land-cover spatial coverage used by NWPCAM 1.6. The USGS developed the LCC database by classifying 1990 National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellite time-series images, with postclassification refinement based on other data sets, including topography, climate, soils, and ecoregions (Eidenshink, 1992). The database is intended to offer flexibility in tailoring data to specific requirements for regional land-cover information.

The raster image has a pixel size of 8-bit, representing an area of 1 km^2. The image contains 2,889 lines and 4,587 samples covering the conterminous 48 states. The projection of the images is Lambert Azimuthal Equal Area. Based on this information, it was possible to extract a specific area from the image into an ASCII file using a routine written in C. This approach allowed portions of the image to be imported, reducing loading and processing time compared to a full-image import into a commercial geographic information systems (GIS) package. The ASCII file was used to generate a point coverage in Arc/Info, which was converted to geographic coordinates in order to process it with existing RF3 coverages.

Each land-use cell was assigned to the nearest routed RF3 reach for subsequent drainage area, stream discharge, and hydrologic routing purposes. Table 4 lists the key fields and field description for the land-use/land-cover data file.

Table 4. Key Fields of the Land-Use/Land-Cover Data File

Field	Description
CELL_ID	Identification number assigned to land-use/land-cover cell for CAFO NWPCAM study
ANDERSON_LEVEL	Code describing type of land-use/land-cover for cell
AG_CELL_FLAG	Marker to designate agricultural land-use/land-cover cells
STCOFIPS	County FIPS code
DIST_FT	Distance from cell centroid to nearest RF3 reach (feet)
RF3RCHID	Nearest RF3 reach ID
RND_ID	Random number generated for agricultural cells
BOD5_EXPORT	BOD5 export coefficient
TSS_EXPORT	TSS export coefficient

The LCC originally contained 27 Anderson Land-Cover Classes. These were compressed into eight land-use categories in the NWPCAM 1.6 system (see Table 5).

Table 5. Anderson and NWPCAM Land-Cover Classes

NWPCAM Land-Cover Class Code (derived)	NWPCAM Land- Cover Category (derived)	Anderson Land-Cover Class Code	Anderson Land-Cover Class Category
1	Agriculture	1	Dryland Cropland and Pasture
1	Agriculture	2	Irrigated Cropland and Pasture
1	Agriculture	3	Mixed Dryland/Irrigated Cropland and Pasture
2	Agriculture/ herbaceous	4	Grassland/Cropland Mosaic
3	Agriculture/ woodland	5	Woodland/Cropland Mosaic
4	Herbaceous	6	Grassland
4	Herbaceous	7	Desert Shrubland
4	Herbaceous	8	Mixed Shrubland/Grassland
4	Herbaceous	9	Chaparral
4	Herbaceous	10	Savanna
5	Forest	11	Northern Deciduous Forest
5	Forest	12	Southeastern Deciduous Forest
5	Forest	13	Western Deciduous Forest

(continued)

Table 5. (continued)

NWPCAM Land-Cover Class Code (derived)	NWPCAM Land- Cover Category (derived)	Anderson Land-Cover Class Code	Anderson Land-Cover Class Category
5	Forest	14	Northern Coniferous Forest
5	Forest	15	Southeastern Coniferous Forest
5	Forest	16	Western Coniferous Forest
5	Forest	17	Western Woodlands
5	Forest	18	Northern Mixed Forest
5	Forest	19	Southeastern Mixed Forest
5	Forest	20	Western Mixed Forest
6	Waterbodies	21	Waterbodies
4	Herbaceous	22	Herbaceous Coastal Wetlands
5	Forest	23	Forested Coastal Wetlands
6	Barren	24	Barren or Sparsely Vegetated
5	Forest	25	Subalpine Forest
7	Tundra	26	Alpine Tundra
8	Urban (derived)	30	Urban

2.1.3 RF3 Hydrologic Data

Stream drainage area, discharge data, and related hydrologic data at the RF3 reach level (RF1 for Hydroregions 8 and 17) are required for hydrologic routing and in-stream nutrient transport and decay processes simulated by NWPCAM 1.6. After the RF3 routing system is established, information regarding the hydrologic (e.g., flow rate) and the hydrodynamic characteristics (e.g., channel depth, channel width, velocity) of each reach are incorporated into the model framework.

The fate of a water quality parameter along a hydrologic network is driven by the time of travel from one reach to the next and kinetic parameters. Time of travel is dependent on reach velocity and segment length. Velocity depends on the flow rate and the channel geometry of the reach. Consequently, the hydraulic routing process of the water quality model largely becomes a system of accounting for discharges, stream geometry, velocity, and travel distances to derive the time of travel. Table 6 lists principal hydrologic data used in NWPCAM 1.6.

2.1.3.1 Stream Drainage Area. To develop drainage areas for each RF3 reach, the land-use coverage was overlain on the RF3 routing framework to associate each land-use cell with the nearest RF3 reach. The number of cells assigned to each reach provides the approximate drainage area in square kilometers for the specific RF3 reach. This value represents the land that contributes direct runoff to the reach versus the runoff received from the immediate upstream reach (i.e., the hydrologically routed runoff).

Table 6. Key Fields of NWPCAM 1.6 Hydrologic Data

Field	Description
RF3RCHID	RF3 Reach ID
CU	8-digit catalog unit
DRAINAGE	Drainage area (km^2)
CUM_DRAIN	Cumulative drainage (km^2)
UNIT_Q	Weighted-average unit discharge for the CU (cfs/km^2)
Q	Discharge (cfs)
N	Manning's n (min = 0.025, max = 0.040)
SLOPE	Average slope in 8-digit catalog unit
WIDTH	Channel width (ft)
DEPTH	Channel depth (ft)
VELOCITY	Reach velocity (ft/s)
TOT	Time of travel (days)

Cumulative drainage area for an RF3 reach represents the land area associated with the reach itself plus the land area of upstream reaches. The cumulative drainage area for a given RF3 reach is calculated by hydrologically routing all reaches in the RF3 file according to the routing sequence number and summing the reach-specific drainage areas as they are routed through the system. For example, the cumulative drainage area of the most headwater reach of a stream simply would be calculated from the land-use cells that are directly associated with that reach. As the routing algorithm moves downstream, the cumulative drainage area for a specific reach would be calculated as the area of the land-use cells that are directly associated with that reach plus the drainage areas of each reach that is hydrologically upstream of the specific reach.

Validation exercises were conducted to verify the drainage area methodology. The drainage area estimates derived from the land-use cells were compared with estimates of drainage area derived from USGS stream gages. USGS stream gages in the HCDN were selected for data comparisons because they represent relatively natural hydrologic conditions and are not influenced by controlled releases from reservoirs. Only gages with a drainage area less than the drainage area of its cataloging unit were selected. This ensured that the discharge data from the same set of HCDN gages could be used for future discharge comparisons.

Each of the HCDN gages was assigned to the nearest RF3 reach based on geographic coordinate information. The drainage area estimate from the HCDN gage was compared with the drainage area estimate for the RF3 reach derived from the land-use/land-cover coverage. Several outliers were initially observed, although further review of the data sets showed that either the HCDN gage had been assigned to the wrong RF3 reach or the RF3 reach had been removed from the RF3 data set because of incomplete data. The analysis indicated close agreement between the two drainage area estimates in the eastern hydroregions (see Figure 2 for a comparison of estimates in Hydroregion 7; $R^2 = 0.995$).

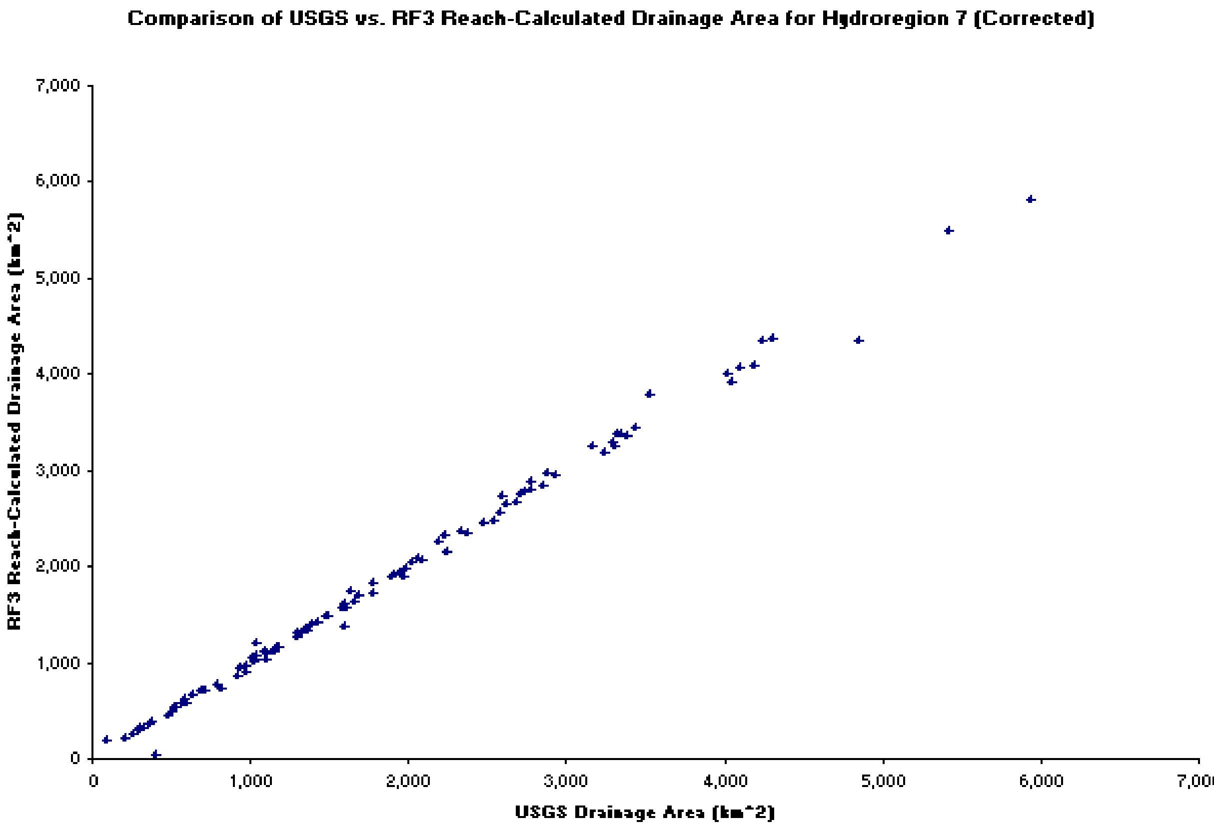

Figure 2. Comparison of drainage area estimates between NWPCAM and HCDN.

2.1.3.2 <u>Discharge Data</u>. Initial comparisons of drainage area were not as favorable in the western hydroregions as in other areas. In the western areas, estimates of routed discharge (i.e., streamflow) in NWPCAM 1.6 were generally greater than the HCDN gage values. Consequently, an attempt was made to match NWPCAM discharge estimates with the HCDN

gage data by incorporating only a percentage of the runoff for intermittent stream reaches. A best fit was selected based on the correlation between NWPCAM estimates and HCDN values (see Table 7).

2.1.3.3 <u>Runoff</u>. Data from the full HCDN network of 1,391gages were used to derive a mean annual unit runoff ($ft^3/sec/km^2$) for each cataloging unit. HCDN gages are selected by USGS as gages that best reflect natural runoff, as opposed to gages that include significant human-influenced streamflows. In general, the HCDN gages require at least 10 years of records to establish mean annual and mean summer flows. A 200-mi maximum search radius from the centroid of the cataloging unit was used to identify the five nearest HCDN gages. In some cases, less than five gages were available within the 200-mi search radius. Mean annual unit runoffs were calculated using a weighted-average technique based on the distance of the HCDN gage from the centroid of the cataloging unit. For each cataloging unit, a mean annual unit runoff was calculated based on mean annual discharge for the HCDN gages. Total discharge for a reach equals the sum of the discharge for the associated land-use cells plus the discharge originating

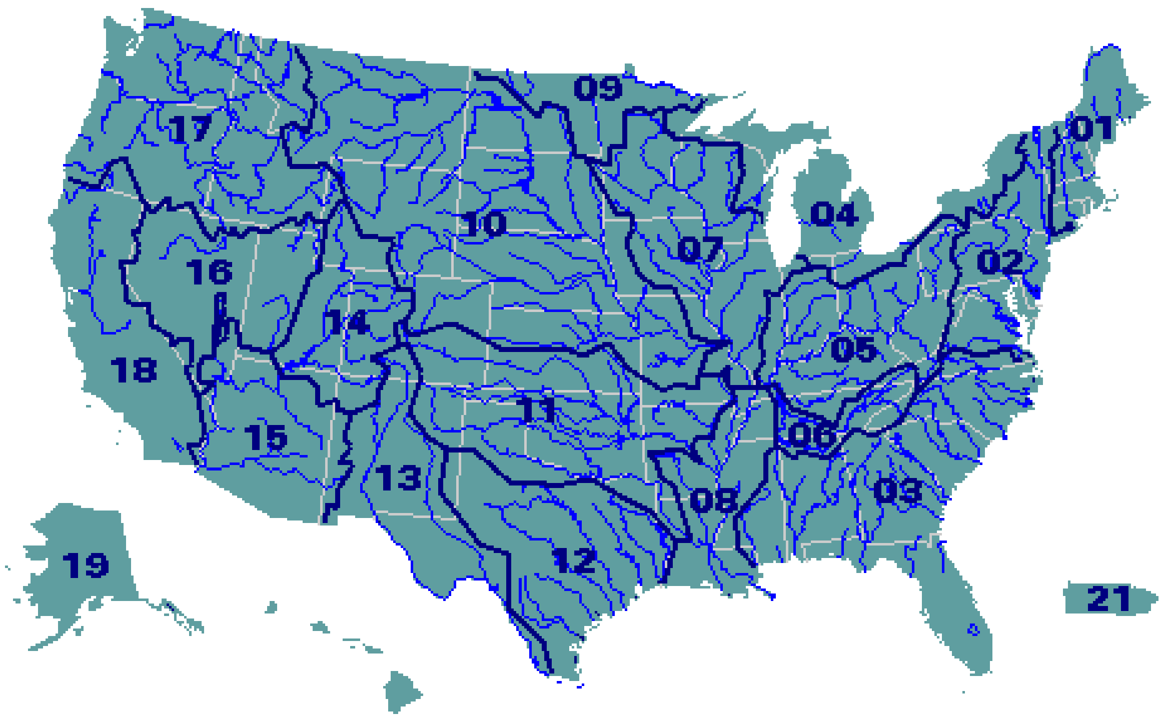

Figure 3. Map of the hydroregions from USGS.

Table 7. Refined Hydrology in the Western Hydroregions

Hydroregion	Contribution from Intermittent Streams to Discharge Estimate
10	10%
11	50%
12	100%
13	10%
14	1%
15	1%
16	1%
17	NA*
18	50%

*NA: Not applicable because routing is based on RF1, so perennial/ intermittent flag is not available.

from upstream reaches. The resulting unit runoffs for each cataloging unit were converted to inches of runoff (see Figure 4) and compared with the USGS runoff contour map for the

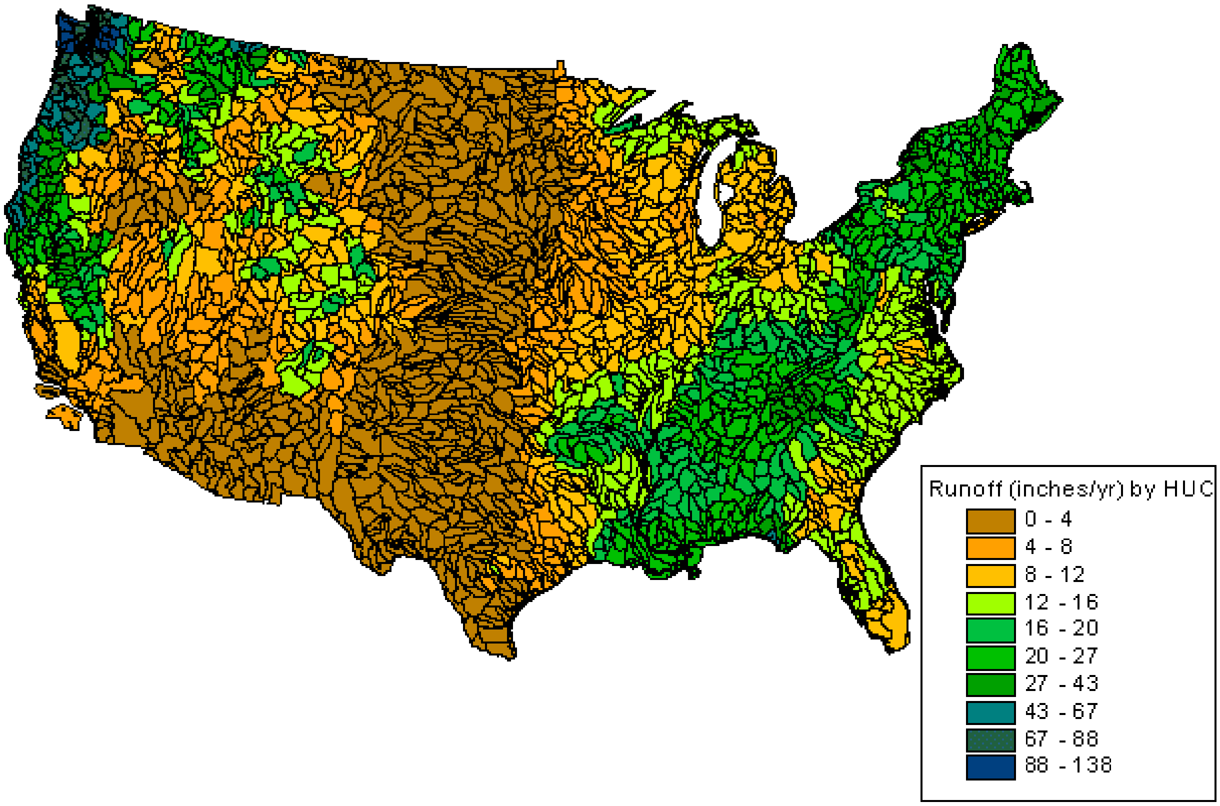

Figure 4. Average annual runoff by cataloging unit.

conterminous 48 states (see Figure 5). A visual comparison of the two maps indicates close agreement between the two sets of data.

2.1.3.4 Velocity. RF3 reach velocity estimates were developed using time-of-travel analyses (Jobson, 1996). Regression equations were developed to relate peak velocity to drainage area, a dimensionless drainage area, slope, discharge, and a dimensionless relative discharge. Jobson presents two velocity estimation methods: one that considers reach slope and one that does not. Based on a comparison between the velocity estimates and an RF1 velocity data set, the RF3 velocity estimates derived without the slope were determined to provide the best match. For most hydroregions, the comparisons were favorable ($R^2 = 0.6$–0.95; RTI, 2001), suggesting that the velocity estimates provide a reasonable basis for use in water quality modeling. The final regression equation used to estimate velocity was

$$VelA\_pnos = 0.02 + (0.051 \times (D'^{\,0.821}_a) \times (Q'^{\,-0.465}_a) \times (Q/D_a)) \quad (1)$$

where

VelA_pnos	=	velocity estimate without considering slope (m/s)
D'_a	=	dimensionless drainage area

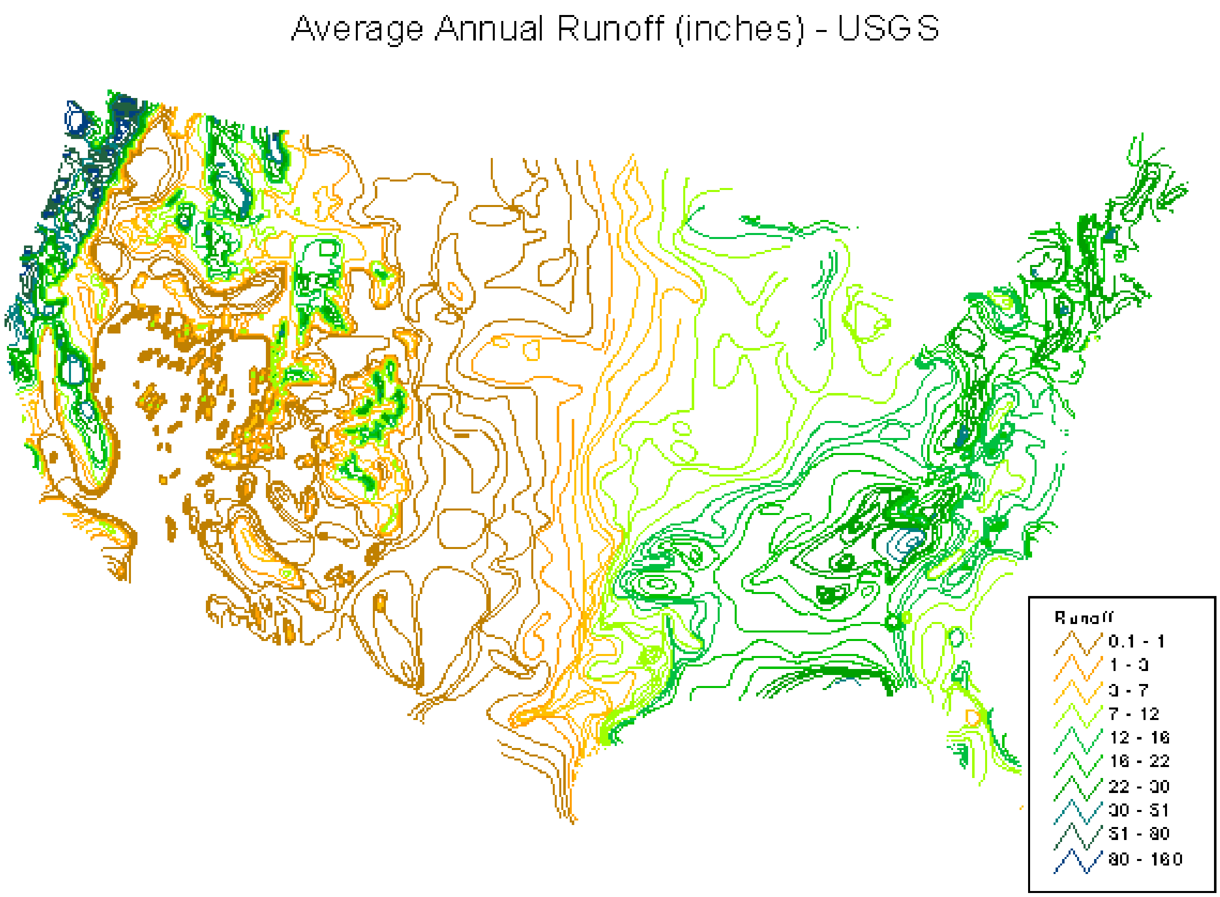

Figure 5. USGS runoff contour map showing average annual runoff for the conterminous 48 states.

Q'_a	=	dimensionless relative discharge
Q	=	reach discharge (m^3/s)
D_a	=	drainage area (m^2).

2.1.3.5 <u>Channel Properties</u>. Because of changes in the process used to determine RF3 reach velocity, a new method was needed for estimating channel geometry. For single-line RF3 reaches, the methodology of Leopold and Maddock (1953) was reviewed to estimate reach width and depth. Channel geometry and mean annual discharge data for more than 100 rivers/streams reported by Leopold and Maddock were used to derive regression equations relating discharge to stream width. The evaluations included consideration of data sets only for rivers with extended periods of data (e.g., 5 years, 10 years, and 18 years). Analysis of the differences between reported widths from the Leopold and Maddock data set and predicted widths from the regression equations were completed. The analysis suggested that the following regression equation provides the best estimates of stream width:

$$W = 5.25 \times (Q_a/V)^{0.5465} \tag{2}$$

where

W	=	width of channel (ft)
Q_a	=	mean annual discharge (cfs)
V	=	velocity (ft/s).

For open waters in RF3Lite (i.e., lakes and wide rivers), stream widths were estimated by dividing the area by one-half of the total circumference. Both area and perimeter data are in the RF3 data set for double-wide reaches. This method approximates the average width along the open water lake or wide-river channel. This approach can understate or overstate average widths based on the shape of the waterbody and the sinuosity of the shoreline. The width estimates in the Upper Mississippi hydroregion (Hydroregion 7) were manually compared with maps and were found to be in close agreement except for one outlier. However, the width estimate, even for the outlier, was within acceptable bounds for modeling purposes.

The method for determining channel depth for all reaches is shown in Equation 3.

$$D = Q / (W \times V) \tag{3}$$

where

D	=	depth (ft)
W	=	channel width (ft)
Q	=	stream flow (ft^3/s)
V	=	stream velocity (ft/s).

2.1.4 Overland Transport Hydrologic Data

The operational foundation for delivering NPS and AFO/CAFO loadings from land cover cells to surface waters is the assumption that these source areas are hydrologically connected to surface waters by surface flow in small channelized systems. NWPCAM 1.6 includes routines to route loadings from land-cover cells to the RF3 network. These modules account for overland transport, decay, and transformation as a function of travel time. Travel time is based on distance from the center of the land-cover cell to the associated RF3 reach, and velocity, which is calculated using standard open-channel flow assumptions. There is assumed to be one open channel from the centroid of each land-cover cell to its nearest RF3 reach.

The flow rates in the open channels were approximated using the unit runoff values estimated from the HCDN network. In addition to estimating flow volume, channel characteristics were estimated as a prerequisite for estimating velocity and time of travel. A log-log relationship between stream flow and channel width was developed based on Keup's methodology (1985):

$$W = 5.27 \times Q^{0.459} \tag{4}$$

where

W	=	channel width (ft)
Q	=	discharge (stream flow in cubic feet per second [cfs]).

Channel depths were calculated based on the classic Manning's *n* formulation for channel resistance analysis. Assuming a rectangular channel cross-section, the following formula was used to calculate stream depth:

$$y_0 = 0.79\ (Q \times n/(W \times (S_0)^{0.5}\ )^{0.6} \tag{5}$$

where

y_0	=	channel depth (ft)
Q	=	discharge (stream flow in cfs)
n	=	Manning's *n* roughness coefficient
W	=	channel width (ft) calculated above
S_0	=	channel slope (ft/ft) (for RF3Lite reaches).

A Manning's *n* of 0.10 was selected to represent weedy, windy, overgrown channels, such as might be found on agricultural lands. This value for Manning's *n* is specific to cell-to-RF3 routing.

Velocity in the channels was calculated as

$$V = Q/(W \times y_0) \times C \tag{6}$$

where

V	=	velocity (ft/sec)
Q	=	the discharge (per km^2) for the HUC
y_0	=	channel depth (ft)
W	=	channel width (ft)
C	=	conversion factor to reconcile units.

Time of travel to the nearest RF3 reach was calculated as

$$TOT = SL/(V \times C) \tag{7}$$

where

TOT	=	overland time of travel (days)
S	=	sinuosity (ft/ft)
L	=	distance from cell center to nearest reach (ft)
V	=	velocity (ft/sec)
C	=	conversion factor = 86,400.

Sinuosity varied on a hydroregion basis and was calculated as the 75th percentile value of the sinuosities for the first-order stream RF3 reaches.

2.1.5 PS Loadings Data Set

Loading data from industrial facilities, municipal facilities, and combined sewer overflows are included in NWPCAM 1.6. These sources are collectively referred to as PS of pollution. Loading data for these sources were obtained from EPA's 1997 Permit Compliance System (PCS), Clean Water Needs Survey (CWNS), and the Industrial Facilities Database (IFD). The databases supplied information on effluent nitrogen, phosphorus, total suspended solids (TSS), 5-day biochemical oxygen demand (BOD), and fecal coliform. CSOs were assigned default values for total nitrogen (TN) and total phosphorus (TP) loadings (U.S. EPA, 2001). Loads from 24,231 industrial facilities, 10,501 municipal facilities, and 617 combined sewer overflows were included in the NWPCAM 1.6 system. Table 8 lists total loads included in NWPCAM 1.6 for the PS category.

Table 8. Total Loadings for PSs*

Source Type	BOD5 load (g/s)	TN load (g/s)	TP load (g/s)	TSS load (g/s)	Fecal Coliform (FEC) Load (MPN/s)
Municipal and Industrial Facilities	58,829	23,460	5,628	214,964	1.96×10^{12}
Combined Sewer Overflows	3,707	643	248	13,613	1.87×10^{14}
Total	62,536	24,103	5,876	228,577	1.89×10^{14}

* i.e., industrial facilities, municipal facilities, and combined sewer overflows

All of the nutrient loadings from the PSs were speciated into inorganic and organic forms based on treatment level (see Table 9; Metcalf & Eddy et al., 1991). CSOs that were not linked to a municipal facility were speciated using the "Raw" factors.

In preparation for the AFO/CAFO modeling process, the PS loads were routed directly to the RF3Lite network in preparation for further in-stream modeling. Table 10 lists the total PS loads at the RF3Lite scale, along with delivery ratios for each component.

2.1.6 NPSs (Non-AFO) Loadings Data Set

AFO loadings to river reaches have typically been included in NWPCAM as part of NPS loadings. In order to evaluate AFO/CAFO regulatory options, they must be a separate source category. An approach was developed to estimate non-AFO/CAFO NPS loadings (Bondelid, Dodd, et al., 1999).

Within each watershed, a simple export coefficient loading model was used to deliver nutrients from NPSs to a reach. Export coefficients are empirical values that describe the loading

Table 9. Speciation Factors for Nitrogen and Phosphorus*

Pollutant Ratio	Treatment Level					
	Raw	Primary	Advanced Primary	Secondary	Advanced Secondary	Tertiary
TKN:TN	1	1	1	0.9	0.7	0.25
NH_3:TN	0.6	0.615	0.615	0.67	0.186	0.138
TON:TN	0.4	0.385	0.385	0.23	0.514	0.112
$(NO_2 + NO_3)$:TN	0	0	0	0.1	0.3	0.75
PO_4:TP	0.625	0.6	0.6	0.75	0.75	0.925
TOP:TP	0.375	0.4	0.4	0.25	0.25	0.075

*Speciation factors are on a mass basis (e.g., mg/L:mg/L)

Table 10. Total Loadings for PSs at the RF3Lite Scale

Parameter	BOD5	TN	TP	TSS	FEC
RF3Lite Load (g/s or MPN/s)	30,149	14,979	3,600	128,885.9	4.32×10^{13}
Delivery Ratio	0.48	0.62	0.61	0.56	0.23

of a given nutrient in terms of mass per unit time per unit area. The analytical specification for export coefficients requires estimates of both the unit loading and the land area within a catchment described in terms of different types or classes of land use or land cover. The analytical model can be summarized as

$$L = \sum (EC_n \bullet A_n) \tag{8}$$

where

L = loading to a reach (kg/yr)
EC_n = export coefficient for category *n* (kg/ha/yr)
A_n = area draining to reach in land use category n (ha)
n = land-cover or -use category.

The principal data sources for this model are (1) the LCC data set; (2) empirically based estimates of export coefficients derived from a national study (Reckhow et al., 1980); and (3) model output from a national study of nutrient sources, transport, and in-stream flux (Smith et al., 1997).

Nutrient loads for NPSs were computed by land-use type by ecoregion based on SPAtially Referenced Regression On Watershed attributes (SPARROW), which is a statistical modeling approach for estimating major nutrient source loadings at a reach scale based on spatially referenced watershed attribute data (Smith et al., 1997). An optimization algorithm was developed to estimate nonmanure loadings by comparing SPARROW nonmanure NPS estimates for cataloging units with NWPCAM modeled outputs.

The first step in regional export coefficient estimation was to determine appropriate ranges for different land-cover classes. The basis of export coefficient estimation was defined as all cataloging units sharing the same predominant ecoregion (see Figure 6). For each ecoregion within a hydroregion, export coefficients were estimated using a genetic optimization routine to find a set of optimal coefficients. The criterion for optimization was minimizing the sum of squared error between predicted (coefficient) and empirically based (SPARROW) cataloging unit level data.

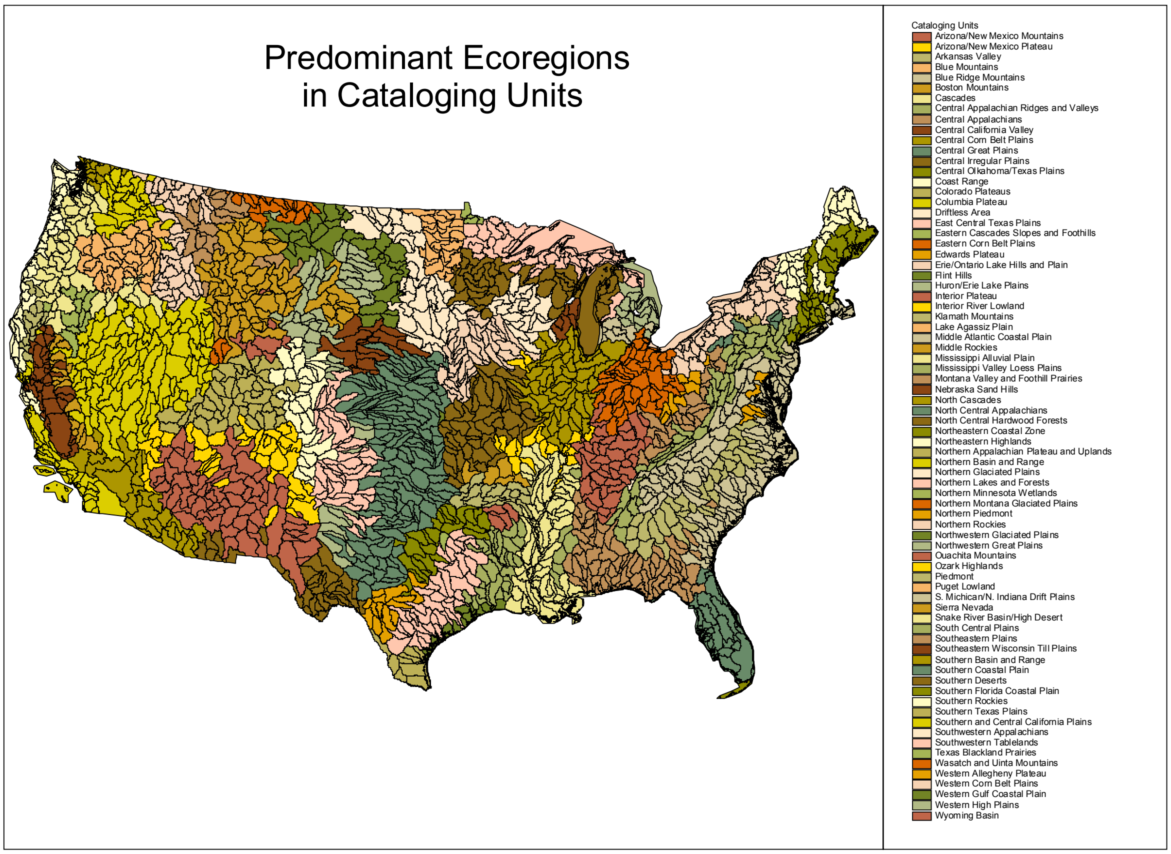

Figure 6. Predominant ecoregions in cataloging units.

Export coefficients for BOD were assigned based on three general land-use categories: agricultural, forest, and urban areas (Thomann and Mueller, 1987; Novotny and Olem, 1994). Typical values for TSS export coefficients were also obtained for the three land-use categories mentioned above (Thomann and Mueller, 1987; Novotny and Olem, 1994). TSS export coefficients on agricultural cells were amended using a generalized revised universal soil loss equation (RUSLE; USDA, 1997). This method allowed spatial variability to be introduced into the TSS NPS loadings. The RUSLE equation estimates average soil loss in the following manner:

$$TSS = R \times K \times L \times S \times C \times P \times 2241.7 \quad (9)$$

where

TSS	=	average soil (TSS) loss (kg/ha/yr)
R	=	rainfall-runoff erosivity factor
K	=	soil erodibility factor
L	=	slope length factor
S	=	slope steepness factor
C	=	cover management factor
P	=	support practice factor (assumed to be 1).

The factors used in the RUSLE vary by climate, soil type, and other physiographic factors. Fifteen representative cities were selected to represent various climates across the United States. The major land resource areas (MLRAs) were then overlaid with RF3 and related to a representative city using latitude/longitude coordinates. The values for *R*, *K*, and *C* were obtained from literature and vary by representative city (U.S. ACE, 1998). *L* and *S* are calculated values that vary with each stream reach, but vary in NWPCAM 1.6 by cataloging unit (USDA, 1997):

$$L = (\lambda/72.6)^m \quad \text{and} \quad S = 10.8 \sin\theta + 0.03 \quad (10)$$

where

λ	=	1,640 ft (the distance from centroid to edge of a land-use cell)
m	=	$\beta/(1 + \beta)$
β	=	$(\sin\theta/0.0896) / (3\sin\theta^{0.8} + 0.56)$
θ	=	arctan (slope).

All of the NPS loadings that discharge to intermittent streams in the western hydroregions were multiplied by the percentage of flow included into the discharge estimates during the validation exercise.

NPS data for fecal coliform and fecal streptococci were not readily available at the national scale. Table 11 shows the total loadings from all NPSs. Data from the STOrage and RETrieval (STORET) database were used to develop default NPS fecal coliform loads by hydroregion. The median fecal coliform concentration was derived from each hydroregion. In areas of high AFO activity, one-half of the median fecal concentration was used to avoid double counting those loads.

Table 11. Total Loadings on Land-Use/Land-Cover Cells for NPSs

Source Type	BOD5 load (g/s)	TN load (g/s)	TP load (g/s)	TSS load (g/s)	FCB load (MPN/s)
NPS	226,526	165,572	12,382	15,033,394	-----

In preparation for the in-stream modeling process, the NPS loads are first routed from land-cover cells to the RF3 network by accounting for overland transport, decay, and transformation. The NPS loads are then routed to the RF3Lite network using in-stream transport, decay, and transformation processes. Table 12 lists the total NPS loads at the RF3 and RF3Lite scales, along with delivery ratios for each component.

Table 12. Total Loadings for NPSs at the RF3 and RF3Lite Scale

Parameter	BOD5 (g/s)	TN (g/s)	TP (g/s)	TSS (g/s)	FCB load (MPN/s)
RF3 Load	170,227	134,388	9,555	11,076,412	-----
Delivery Ratio	0.75	0.81	0.77	0.74	-----
RF3Lite Load	163,237	131,775	9,366	10,105,756	5.343×10^{10}
Delivery Ratio	0.72	0.80	0.76	0.67	-----

2.2 Kinetics

Overland transport modeling occurs for every land-cover cell to its associated RF3 reach. In-stream modeling is conducted on a reach-by-reach basis. The pollutant concentration at the upmost point of a reach or open channel is a function of the mixing and dilution of the mass load from an upstream reach plus any pollution sources. The upstream boundary concentration (C_o) is obtained from a steady-state mass balance dilution calculation in Equation 11:

$$C_o = [(Q_u C_u) + (Q_e C_e) + (Q_t C_t)] / [(Q_u + Q_e + Q_t)] \tag{11}$$

where

C_o = Concentration at beginning of the reach
Q_u = upstream stream flow entering reach
C_u = concentration from upstream reach
Q_e = effluent flow of PS
C_e = effluent concentration of PS constituent
Q_t = tributary flow of PS
C_t = tributary concentration of constituent.

The fate of nutrients and pollutants during overland transport and in-stream transport is driven by first-order decay kinetics based on the following equation:

$$\frac{dc}{dt} = -K * c \tag{12}$$

where

dc/dt = the instantaneous change in pollutant concentration

K	=	decay rate (1/d)
c	=	pollutant concentration (mg/L).

The closed-form solution of this simple differential equation is

$$C_f = \quad C_i \times e^{(-Kt)} \tag{13}$$

where

C_i = concentration (mg/L) at time 0
C_f = concentration (mg/L) at time *t* (d).

Extensive experience from a large number of studies has shown that the first-order decay process can be adequate for modeling many of the complex physical and biological processes that occur in water. The decay rate is generally based on field measurements, other modeling studies, or calibration of the model. Decay rates for biological processes tend to be temperature dependent. For NWPCAM 1.6, temperature adjustments to decay rates were adopted from U.S. EPA (1985; see Equation 13).

$$K(T) = K(20) \times \theta^{(T-20)} \tag{14}$$

where

K(T)	=	the decay coefficient at the average water temperature
K(20)	=	the decay coefficient at 20° Celsius
θ	=	temperature correction factor = 1.07 for FCB
T	=	average water temperature.

2.2.1 Carbonaceous Biochemical Oxygen Demand

Although BOD5 is typically reported as the sole indicator of oxygen-demanding material in wastewater, streams, and rivers, the biochemical reactions that determine the actual consumption of dissolved oxygen in these waters are not completed within a 5-day incubation period. The true measure of the long-term oxygen demand of the carbonaceous and nitrogenous materials in wastewater and natural waters can be determined only by continuing the incubation period for longer than 5 days.

Ultimate carbonaceous biochemical oxygen demand (CBODU) is defined as the oxygen equivalent needed for complete stabilization of organic carbon in water and wastewater. Depending on the type of PS or NPS load, ratios of CBODU to BOD5 are used to convert effluent loading data compiled as BOD5 to CBODU required for the model. NWPCAM 1.6 assumes a ratio of 3 to convert NPSs of BOD5 into CBODU. Ratios for PSs vary by treatment level (see Table 13).

The decay rate for CBODU was set to 0.075 day^{-1}.

Table 13. CBODU:BOD5 Ratios for PSs

Treatment Level	CBODU:BOD5 Ratio
Raw	1.2
Primary	1.6
Advanced Primary	1.6
Secondary	2.84
Advanced Secondary	2.84
Tertiary	3.00

2.2.2 Nitrogen Species

In the sequential nitrification reactions for the oxidation of ammonia to nitrite and nitrate, oxygen is consumed. In the breakdown of organic matter, organic nitrogen is hydrolyzed to ammonia. The amount of oxygen required for nitrification is considered as the nitrogenous biochemical oxygen demand (NBOD). External sources of total organic nitrogen and ammonia in the model are derived from inputs from PSs and NPSs. The loss of nitrogen from a waterbody is determined by the complete bacterial oxidation of ammonia to nitrate, hydrolysis of organic nitrogen, and physical settling of the particulate fraction of organic nitrogen. As a product of sediment diagenesis, regeneration of ammonia in the sediment bed serves as a source term for oxidizable nitrogen by the mass transfer of ammonia from the sediment bed back into the water column.

TN decay coefficients are based on the SPARROW model. As mentioned earlier, SPARROW is a statistical tool developed by USGS for estimating major nutrient source loadings at a reach scale (Smith et al., 1997). This study suggests three values for decay coefficients that vary for different flow ranges (see Table 14).

Table 14. SPARROW Coefficients

Flow regime	TN decay rate (day^{-1})	Flow regime	TP decay rate (day^{-1})
< 1,000 ft^3/s	0.3842	< 1,000 ft^3/s	0.2680
> 1,000 ft^3/s and < 10,000 ft^3/s	0.1227	> 1,000 ft^3/s	0.0956
> 10,000 ft^3/s	0.0408	Lake	0.3586

The following transformations between nitrogen species are considered: hydrolysis of total organic nitrogen to ammonia, and oxidation of ammonia to nitrate. Total fluxes of nitrogen species at a given time (t_1) therefore become

$$\begin{aligned} NO_3\,(t_1) &= NO_3\,(t_0) + NO_{3}\_NH_3 \\ NH_3\,(t_1) &= NH_3\,(t_0) + NH_{3}\_TON - NO_{3}\_NH_3 \\ TON\,(t_1) &= TON(t_0) - NH_{3}\_TON \end{aligned} \tag{15}$$

where

$NO_3\ (t_0)$	=	nitrate concentration at time t_0
$NH_3\ (t_0)$	=	ammonia concentration at time t_0
$TON(t_0)$	=	total organic nitrogen concentration at time t_0
$NO_3\_NH_3$	=	nitrate formed from ammonia during t_0 to t_1
NH_3_TON	=	ammonia formed from total organic nitrogen during t_0 to t_1.

The kinetic coefficients used to transform the nitrogen species are shown in Table 15 (U.S. EPA, 1985).

Table 15. Kinetic Parameters for Nitrogen Species

Species	Kinetic Coefficient (day^{-1}; 20°C)	Temperature Correction Factor
Nitrate	0.100	1.045
Ammonia	0.120	1.080
Total Organic Nitrogen	0.075	1.080

2.2.3 Phosphorus Species

TP decay coefficients are also based on the SPARROW model. The model was calibrated using ambient phosphorus flux data. The SPARROW study suggests three values for decay coefficients that vary for different flow ranges (see Table 14).

The NWPCAM 1.6 model accounts for the transformation of total organic phosphorus to phosphate. The fluxes of phosphorus species at a given time (t_1) therefore become:

$$\begin{aligned} PO_4\ (t_1) &= PO_4\ (t_0) + PO_4\_TOP \\ TOP\ (t_1) &= TOP(t_0) - PO_4\_TOP \end{aligned} \tag{16}$$

where

$PO_4\ (t_0)$	=	phosphate concentration at time t_0
$TOP(t_0)$	=	total organic phosphorus concentration at time t_0
PO_4_TOP	=	phosphate formed from total organic phosphorus during t_0 to t_1.

The kinetic coefficient used to transform total organic phosphorus into phosphate was set at 0.03 day^{-1} (U.S. EPA, 1985).

2.2.4 Dissolved Oxygen

Dissolved oxygen (DO) is included in the model framework as a key indicator of water quality for the protection of aquatic biota. DO levels are also directly related to policy scenarios that drive municipal and industrial effluent loading rates of carbonaceous (CBODU) and nitrogenous (TKN) oxygen-demanding materials. Sources of DO that add oxygen to surface waters include atmospheric reaeration and photosynthetic oxygen production from algae, macrophytes, and periphyton. DO is lost from surface waters by respiration of algae, macrophytes, and periphyton; biochemical decomposition of organic carbon (i.e., CBODU); nitrification of ammonia; and consumption of oxygen in the sediment bed. The photosynthetic gains (P) and respiratory losses (R) from aquatic plants are assumed to balance (i.e., P - R = 0 or P = R).

DO concentrations are dependent on CBODU and ammonia concentrations, because the latter account for the carbonaceous and nitrogenous oxygen demands. The solution for DO may also be given in terms of the DO deficit, or departure from the oxygen saturation concentration.

The solution for the spatial distribution of oxygen deficit, *D(x)*, is taken from Thomann and Mueller (1987) and given in Equation 17 for oxygen balance:

The components of the oxygen balance equation (17) are as follows:

(a) the initial value of the oxygen deficit
(b) PS of CBODU
(c) PS of oxidizable nitrogen
(d) distributed source of ammonia load with no significant addition to river flow
(e) input due to distributed source from algal gross photosynthesis
(f) deficit due to distributed sink from algal respiration
(g) deficit due to distributed sink from sediment oxygen demand

$$D(x) = D_o \exp\left(-K_a \frac{x}{U}\right) \tag{17a}$$

$$+ \left(\frac{K_d}{K_a - K_r}\left[\exp\left(-K_r \frac{x}{U}\right) - \exp\left(-K_a \frac{x}{U}\right)\right]\right) L_o \tag{17b}$$

$$+ \left(\frac{K_n}{K_a - K_n}\left[\exp\left(-K_n \frac{x}{U}\right) - \exp\left(-K_a \frac{x}{U}\right)\right]\right) N_o a_n \tag{17c}$$

$$+ \left(\frac{K_n}{K_a K_n}\left[1 - \exp\left(-K_a \frac{x}{U}\right)\right] - \left(\frac{K_n}{(K_a - K_n)K_n}\left[\exp\left(-K_n \frac{x}{U}\right) - \exp\left(-K_a \frac{x}{U}\right)\right]\right)\right) S_{am} a_n \tag{17d}$$

$$- \left[1 - \exp\left(-K_a \frac{x}{U}\right)\right]\left(\frac{P_a}{K_a}\right) \tag{17e}$$

$$+ \left[1 - \exp\left(-K_a \frac{x}{U}\right)\right]\left(\frac{R_a}{K_a}\right) \tag{17 f}$$

$$+ \left[1 - \exp\left(-K_a \frac{x}{U}\right)\right]\left(\frac{S_B}{K_a H}\right) \tag{17g}$$

where

$D(x)$	=	oxygen deficit along longitudinal distance of river
D_o	=	initial oxygen deficit at upstream end of a segment
K_a	=	atmospheric reaeration coefficient
x	=	longitudinal distance in direction of flow
U	=	freshwater stream velocity
K_d	=	CBOD decomposition rate
K_r	=	CBOD removal rate
L_o	=	initial CBODU concentration at upstream end of segment
N_o	=	initial TKN concentration at upstream end of segment
K_n	=	nitrification rate
S_{am}	=	distributed source of ammonia from sediments
P_a	=	daily average gross photosynthetic oxygen production ($P_a = R_a$)
R_a	=	algal respiration rate ($R_a = P_a$)
S_B	=	sediment oxygen demand
H	=	depth of river segment
a_n	=	oxygen to nitrogen stoichiometric ratio (4.57 g O_2/g N).

All reaction rates are computed for the ambient water temperature (T, °C).

After computation of the oxygen deficit, *D(x)*, the DO concentration is computed using Equation 18:

$$DO(x) = [C_s - D(x)] \tag{18}$$

where

C_s	=	dissolved oxygen saturation concentration
$D(x)$	=	oxygen deficit along longitudinal distance of rivers.

The DO saturation concentration *(C_s [S,T, E_{msl}])* depends on water temperature, salt concentration, and elevation above mean sea level and is computed from relationships given by Thomann and Mueller (1987) and Chapra (1997).

The effect of water temperature on oxygen saturation *(O_{sf})* is computed with Equation 19:

$$\text{In } 0_{sf} = -139.34411 + \frac{1.5757\text{-}01 \times 10^5}{T_a} - \frac{6.642308 \times 10^7}{T_a^2} + \frac{1.243800 \times 10^{10}}{T_a^3} - \frac{86.621949 \times 10^{11}}{T_a^4} \tag{19}$$

where

T_a	=	absolute temperature (degrees K)
T	=	temperature (°C)

where T_a is computed from Equation 20:

$$T_a \quad = \quad T + 273.15. \tag{20}$$

The effect of salt on oxygen saturation *(O_{ss})* is computed using Equation 21:

$$\text{In } 0_{sf} = \text{In } 0_{sf} - S \left(1.7674 \times 10^{-2} - \frac{1.0754 \times 10^{1}}{T_a} + \frac{2.1407 \times 10^{3}}{T_a^{2}} \right) \tag{21}$$

where

S = salinity (g L^{-1}).

Using data extracted from STORET, the spatial distribution of chlorides is represented as a mean summer forcing function with summary statistics of chlorides assigned to RF3 reaches as catalog unit mean values. Chloride levels (as mg/L) are converted to salinity (S, as g/L) to estimate oxygen saturation using Equation 22:

$$S \quad = \quad 0.03 + 1.80655 \times 10^{-3} \, [Cl^{-}] \tag{22}$$

The effect of elevation on the temperature *(T)* and salt-dependent DO saturation *(O_{sp})* is computed from a formulation given by Chapra (1997) using Equation 23:

$$O_{sp} \quad = \quad (O_{sf} + O_{ss}) \, [1 - 114.8 \, E_{MSL})] \tag{23}$$

where

O_{sf} = temperature-dependent oxygen saturation (mg/L)
O_{ss} = salt-dependent oxygen saturation (mg/L)
E_{MSL} = mean elevation above sea level (m).

For headwater start reaches, 100 percent oxygen saturation is assumed so that the initial deficit is zero. For inflows across the upstream boundary and tributary inflows, the oxygen deficit is computed, stored, and assigned from upstream solutions of the model. For PSs, characteristic oxygen concentrations are assigned.

Loadings for groundwater pollution are not considered in NWPCAM because of a lack of nationally available data. Groundwater flows are implicitly taken into account in the HCDN-derived streamflow estimates.

Oxygen transfer from the air to the surface layer of a waterbody depends on water temperature and turbulence due to velocity in the river, turbulence due to wind mixing, and any turbulence contributed by water falling over waterfalls and dams. For this simplified model, the atmospheric contributions from wind mixing, waterfalls, and dams are not considered. The atmospheric reaeration coefficient *(K_a)* is determined using the method of Covar (1976) presented in Bowie et al. (1985) and adopted for the Wasp5-Eutro5 model (Ambrose et al., 1993). The method computes reaeration as a function of velocity and depth using formulations developed by Owens et al. (1964), Churchill et al. (1962), and O'Connor and Dobbins (1958) for different categories of streams and rivers. The selection of the specific formulation is governed by depth and velocity assigned to the RF3 reach. The computation of K_a is given in Equation 24:

$$K_a = a\,U^b\,H^c \tag{24}$$

where

a, b, c = coefficients for depth and velocity
U = velocity (m/s or ft/s)
H = depth (m or ft).

The lower and upper ranges for depth *(H)* and velocity *(U)* and the numerical values of the coefficients (*a, b,* and *c*) for the three formulations are given for both metric and English units in Table 16.

Table 16. Depth (H) and Velocities (U) Ranges, Reaeration Formulations, and Coefficients for Owens et al., Churchill, and O'Connor-Dobbins (Chapra, 1997; Ambrose et al., 1993)

		Metric Units (U as m s^{-1}, H as m)	English Units (U as ft s^{-1}, H as ft)
Owens et al. (1964)			
(Depth: Shallow streams)			
H	=	0.12< H < 3.3	0.4< H < 11
U	=	0.03< U < 1.52	0.1< U < 5
a	=	5.32	21.6
b	=	0.67	0.67
c	=	-1.85	-1.85
Churchill (1962)			
(Depth: Moderate to deep; fast velocity)			
H	=	0.61 < H < 3.3	2 < H < 11
U	=	0.55 < U < 1.52	1.8 < U <5
a	=	5.026	11.6
b	=	1.0	1.0
c	=	-1.67	-1.67
O'Connor and Dobbins (1958)			
(Depth: Moderate to deep; low to moderate velocity)			
H	=	0.3 < H < 9.1	1 < H < 30
U	=	0.15< U < 0.49	0.5 < U < 1.6
a	=	3.93	12.9
b	=	0.5	0.5
c	=	-1.5	-1.5

The atmospheric reaeration rate is adjusted for ambient water temperature according to the following relationship using a temperature correction factor of 1.024.

The importance of the decomposition of organic matter deposited in the sediment bed has been understood since oxygen balance models were developed during the 1960s. Water quality models typically define spatially dependent rates of sediment oxygen demand (SOD) as a zero-order, external forcing function specified as input data to a model (e.g., Qual2E, Brown and Barnwell, 1987; Wasp5-Eutro5, Ambrose et al., 1993). In using NWPCAM to simulate water quality under reduced loading conditions as a result of control alternatives, the effects of loadings reductions on SOD conditions was problematic since no reliable methods were available to link changes in organic matter deposition to changes in SOD. Where the control alternatives were not expected to greatly alter the loading of particulate organic matter to the sediments, an assumption of no change in the SOD was reasonable.

Incorporating a full SOD model is far beyond the scope of NWPCAM. Rather, a simplified SOD model was adopted based on the analysis of Di Toro et al. (1990). This work showed that the SOD exerted by decomposition of particulate organic carbon in the sediments is dependent on the square root of the loading of particulate organic carbon to the sediments. This theoretical result of the SOD model has been confirmed in analyses of published data sets and contemporary field measurements (Di Toro et al., 1990). SOD rates at 20 °C are assigned to RF3 reaches as follows:

- RF3 Reaches Not Affected by PS: 0.5 g O_2 $m^{-2}day^{-1}$
- RF3 Reaches Assigned PS Loads: 1.5 g O_2 $m^{-2}day^{-1}$.

2.2.5 Total Suspended Solids (TSS)

Suspended solids are included in the model framework as an indicator of water clarity. Solids are introduced into surface waters by naturally occurring geomorphological processes and anthropogenic loading from PSs and land-use-influenced NPSs. In streams and rivers, the distribution of solids suspended in the water column is determined by the particle size characteristics of cohesive and noncohesive solids, hydrodynamics, and the particle size-dependent balance between deposition and bottom shear-induced resuspension.

The representation of suspended solids in NWPCAM is highly simplified. A single size class of solids is used to define both the inorganic and organic components of TSS with no distinction made between cohesive and noncohesive solids. No attempt was made to account for the solids content of a sediment bed that can be resuspended back into the water column under high-flow conditions of erosion because (1) national-scale data are not available to characterize the spatial distribution of solids in the sediment bed or to distinguish between cohesive and noncohesive size classes either in the water column or the bed; and (2) any representation of resuspension based on bottom shear stresses and velocities computed from the simplified flow balance would introduce an enormous amount of uncertainty into the model framework. The simplified model for TSS, based on no interaction of solids between the water column and the sediment bed, assumes a "one-way loss of solids to the bed" (Chapra, 1997).

Sources of suspended solids in the model are derived from external inputs from PSs and NPSs. The balance between deposition and resuspension is represented in the model as a simple, first-order loss term governed by the settling velocity assigned to the single size class of solids and the depth of the water column. As phosphorus is generally bound to sediments, the decay rate for phosphorus is related to the deposition rate of sediments. Settling velocities for TSS were based on the national SPARROW model (Smith et al., 1997).

2.2.6 Pathogens

Fecal coliform bacteria (FCB), used as an indicator for the public health risk of exposure to waterborne pathogens, are present in surface waters primarily from sources accounted for by direct discharges from municipal and industrial wastewater facilities, CSOs, and watershed runoff from urban and rural land uses. Bacteria are lost from the water column primarily by mortality. Settling and/or resuspension of bacteria sorbed onto particles are also processes that can influence the density of bacteria. The loss of FCB is represented in the model as a simple, first-order lumped mortality term. The FCB decay coefficient at 20° Celsius was set to 0.8 day^{-1}. A temperature correction factor of 1.07 is employed by NWPCAM 1.6.

Fecal streptococci (FS) are also modeled by NWPCAM 1.6 for the AFO/CAFO modeling process. The FS decay coefficient was set at 0.168 day^{-1}.

2.2.7 Other Processes

NWPCAM does not simulate the effects of nutrients on primary production, and the subsequent effects of primary production on turbidity, dissolved oxygen, and BOD. Thus, it is fair to say that the water quality benefits of reductions in nutrient loadings may be underestimated. EPA seeks to improve representation of these processes in future development of the NWPCAM model.